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Helmet-mounted display targeting symbology color coding: An air-to-air scenario evaluation

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ABSTRACT

Laboratory and flight test evaluations have consistently demonstrated the potential for helmet-mounted display (HMD) presented information to enhance air combat performance. The Air Force Research Laboratory's (AFRL's) Helmet-Mounted Sight Plus (HMS+) program seeks to provide further enhancement by enabling the presentation of multi-color symbology and sensor imagery. To take proper advantage of color-capable HMDs, systematic evaluations must be conducted to identify the best color-coding techniques. The experiment described here is the second we have conducted to address this need. The first experiment identified the better of two competing color coding strategies for air-to-air weapons symbology and indicated that pilots preferred the color codes over an otherwise equivalent monochrome baseline. The present experiment compared the "winning" color code to the monochrome baseline during trials of a complex multi-player air-to-air weapon delivery scenario. Twelve fighter pilots representing three different countries (U.S., U.K., and Sweden) flew simulator trials that included target identification, intercept, attack, missile launch, and defensive maneuvering tasks. Participants' subjective feedback and performance data indicated a preference for color coded symbology.

Keywords: air-to-air, airborne, coding, color, combat, display, helmet, HMD, symbology, targeting.

1. INTRODUCTION

The US Air Force Research Laboratory's Helmet-Mounted Sight Plus (HMS+) program is developing a color helmet-mounted display (HMD) to enhance information conveyance to the pilot. HMS+ is essentially a color-capable version of the Visually-Coupled Acquisition and Targeting System (VCATS) HMD, which has been developed mainly to support missile aiming over a large range of pilot head positions and orientations. This aiming ability is a major advantage of HMDs over head-up displays (HUDs), as Barns (1989) points out: "The target is outside the HUD field-of-view during most tactical maneuvers and offsets. The farther off the target can be detected and tracked, the more effective the intercept tactics can be."[1] The potential benefits of HMD-presented information have been demonstrated in the laboratory and in flight tests[2,3,4].

A full-color capability may be desired ultimately for more versatile HMDs, but the HMS+ program is developing a two-primary, red + green (RG) HMD using a subtractive-color active-matrix liquid-crystal display (AMLCD) as the image source[5,6]. Subtractive-color AMLCD technology has been selected because it provides better image quality than conventional additive-color AMLCDs in this application[7]. An RG display can produce reds, greens, and all the intervening hues (i.e., oranges and yellows) but not whites, grays, blues, purples, or cyans. The RG color repertoire should be adequate, though, given the limited intended application for HMS+. Furthermore, for a subtractive-color AMLCD, the use of RG instead of full color reduces the manufacturing cost by 39% and increases the display's transmittance two to four times[8].

In a previous study, we developed two color-coded versions of the VCATS weapons symbology using the RG color repertoire[9]. Six US Air Force fighter pilots with HUD and air-to-air weapon delivery experience evaluated the color codes after testing them while flying an air-to-air scenario in a simulator. All six pilots preferred the color-coded symbology to the monochrome VCATS baseline. Furthermore, and perhaps surprisingly, a "red means shoot" color-coding strategy (which involved a progression from green to red as an indication of shoot-criteria satisfaction) was preferred unanimously to a "green means go" strategy (which involved a red-to-green progression).

Although the general merits of color coding—particularly for speeding visual search—are well documented[10,11,12], it is not obvious that color coding HMD air-to-air weapons symbology should have measurable and important performance benefits, pilot preference notwithstanding. The purpose of the present experiment was to determine whether any such benefits can be demonstrated for the "red means shoot" code.

2. METHOD

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2.1 Participants

Twelve volunteer military pilots from the US, UK, and Sweden participated. Their mean flight time was 2448 hours. Ten pilots had experience in HUD-equipped fighters, four reported in-flight HMD experience, and nine had air-to-air missile launch experience.

2.3 Apparatus

We used a 40-foot (12-m) diameter projection dome with an F-16 cockpit mockup that included a single throttle, force-type side stick controller, HUD, radar scope, attitude indicator, and horizontal situation indicator. The simulation software used an F-16 aerodynamic model. The dome provided a 150-degree horizontal by 70-degree vertical visual scene, which was produced by six color CRT projectors. The HMD was simulated by drawing the symbology on the dome, superimposed additively on the outside scene by the graphics processor, within a 20-degree circular field of view (FOV) that was centered about the participant's line of sight (LOS). The LOS was measured by a magnetic head tracker. The HMD was blanked when the tracker indicated that the participant was looking down at the panel instruments or HUD, to simulate the action of a real cockpit HMD. A black-sky outside-world scene was used, to maximize the HMD's luminance contrast. The luminances of the red, green, and yellow symbols were 0.20, 0.65, and 0.85 cd/m^2, respectively, when they were measured against the black sky. Symbol contrast ratios ranged from 0.5 to 3.7, depending on the combination of symbol color and background.

2.4 HMD symbology and color coding

We used the VCATS symbology (see Figure 1), which is similar to existing HUD symbology and therefore familiar for most tactical pilots. It was green in our monochrome conditions. It includes several functionality groups, but only those relating to target location, tracking, and weapons deployment were color coded so we discuss only these groups below. Geiselman et al. describes the symbology more completely[9]. For this experiment, the color-coding approach was as follows: Red indicated a weapon-ready-for-launch condition. The more things turned red, the closer the selected weapon was to a firing solution. The design logic was that a weapon-ready state is a dangerous condition for the weapon's intended recipient (i.e., it is an exocentric threat). Thus, red indicated both a ready state and a danger state: "Use extreme caution because the missile is likely to hit what is tracking." Green was the default status color, as well as an "out-of-limits" indication. Yellow indicated a state approaching either acceptable or unacceptable limits. Identification symbology was also color coded. To summarize:

Green = Normal status/out of limits and *friendly* identification.
Yellow = Approaching limit and *unknown* identification.
Red = Criteria met (The more red, the greater the probability of success) and *hostile* identification.

The constant green components included the ownship, LOS, and general information groups. Green was chosen as the baseline color because it is the conventional HMD symbology color. The radar LOS circle was yellow to represent a ready state.

TD box group. The target designator (TD) box symbols showed an extrapolated primary designated target (PDT) LOS when the target was within the HMD FOV; that is, within a 10-degree radius of the HMD center point. This symbology, like all other targeting-specific symbology, was present only when a radar PDT was established. The box symbols were superimposed on the target location in the outside scene. The TD box was replaced by a target locator line whenever the target was within the sensor field-of-regard but located beyond the HMD FOV. Only one PDT could exist at a time. Information around the box included a shape-coded identification friend or foe (IFF) symbol on the left side. Above the box, an alphanumeric readout showed either target recognition information (e.g., aircraft model identification) or the number of degrees (if fewer than 10) before the target would reach the onboard radar's maximum coverage angle. (This number is known commonly as "degrees before break-lock.") Alphanumeric indications of target range and altitude were attached to the right side of the box. The bottom side was reserved for the appearance of a star-type shoot-cue symbol when the launch parameters for the current selected weapon were satisfied.

The color coding for the TD box group varied between green and red depending on the missile launch solution. The TD box was green if the PDT was outside the missile's maximum or minimum allowable launch ranges. Within the maximum flight ($Rmax_1$) and maximum terminal phase maneuvering ($Rmax_2$) PDT ranges, the TD box changed continuously from green to yellow. Within $Rmax_2$, the TD box snapped to red. These color changes indicated the transition of the PDT from out-of-range to within minimal launch parameters and, finally, to within a high probability-of-success launch range. The TD box remained red within the $Rmax_2$ and minimum launch (Rmin) ranges. Inside the Rmin range, the TD box snapped back

to green to indicate the return to an out-of-limits state. Additionally, the inside-Rmin state was indicated by the presentation of a green break “X” symbol (not shown in Figure 1), drawn across the center of the HMD FOV. Presentation of the TD-box- (and locator-line-; see below) associated shoot cue symbol indicated a within-good-launch-parameters state; therefore, the shoot cue symbol was always red. The degrees-before-break-lock alphanumeric associated with the TD box and locator line was always yellow because this information, when it appeared, indicated an approaching-limits condition. Symbols representing friendly IFFs were green, unknown targets were yellow, and hostile targets were red; this system conforms with conventional IFF color coding.

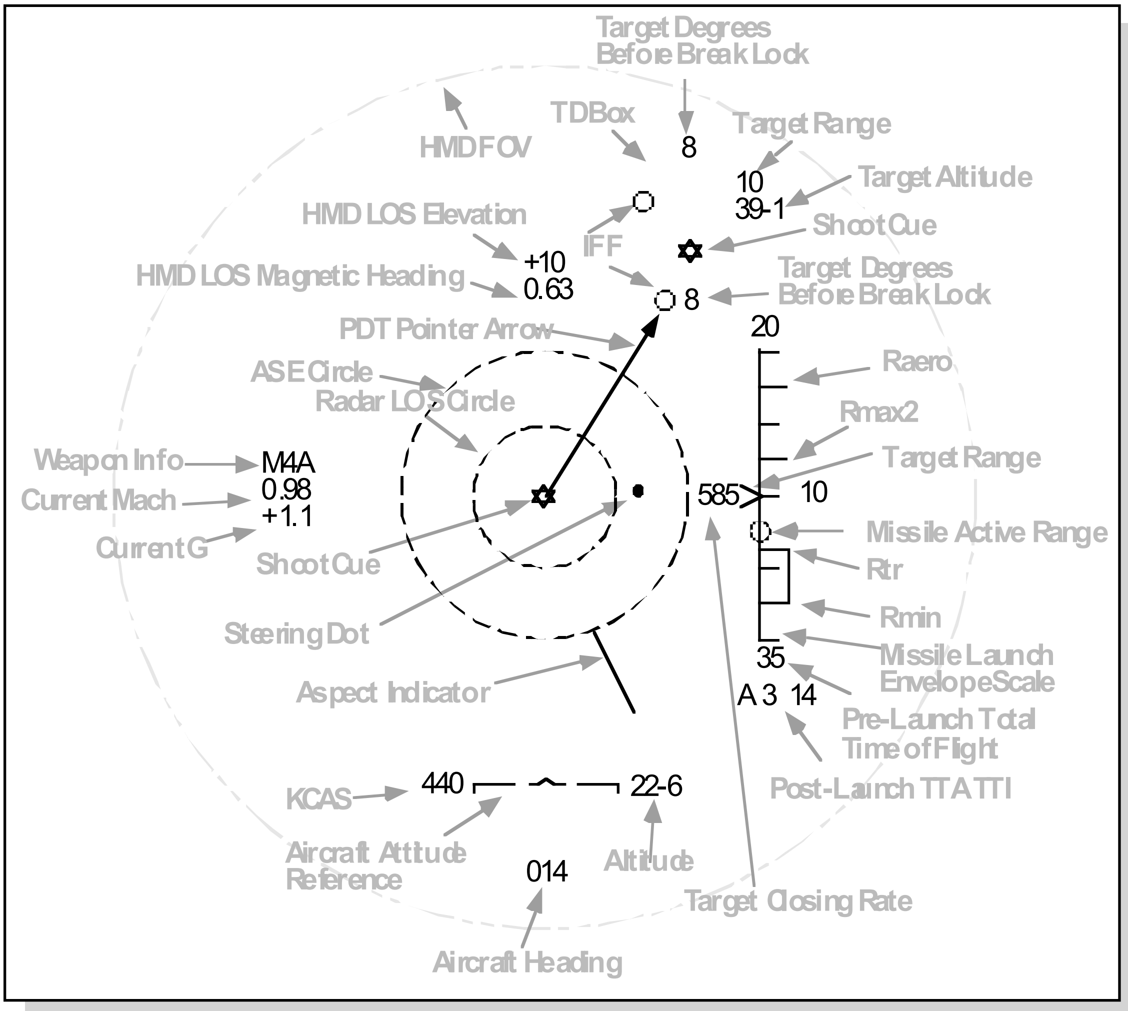


Figure 1. Composite VCATS symbol set with explanatory labels.

<u>Target locator line group</u>. A target locator line showed the continuously computed combined azimuth and elevation vector to the PDT LOS when the PDT was located outside the HMD FOV. The locator line and TD box did not coexist. Accordingly, the line also had IFF, degrees before break-lock, and shoot cue symbology attached to it. The line was anchored at the center of the HMD FOV and radiated out toward the edge of the HMD FOV. The outside end of the locator line was a solid arrowhead. The length of the line changed dynamically in proportion to the angular difference between the HMD LOS and the PDT location, up to 45 degrees. Beyond 45 degrees, the line was drawn at its maximum length of 7.8 degrees. Between 45 degrees and the point where the target crossed within the HMD FOV, the locator line shortened to its minimum length of approximately 2 degrees. A shape-coded IFF symbol was attached to the locator line arrowhead. A circle indicated a friendly return, an “X” indicated an unidentified return, and a diamond indicated a hostile target. A degrees-before-break-lock readout was displayed next to the IFF symbol if the PDT was within 10 degrees of the maximum radar coverage. A shoot cue was displayed at the locator line anchor when the launch parameters for the selected weapon were satisfied for the PDT. The locator-line’s color-coding matched the TD box’s.

ASE circle group. The allowable steering error (ASE) circle was a boresight-referenced repeater of the same symbology presented on the HUD. A comparison of the dynamic steering dot to the edge of the ASE circle indicated the instantaneous quality of the missile launch relative to the weapon's lateral and vertical limitations. The radial aspect indicator line represented the PDT's aspect angle relative to the ownship flight path.

The ASE circle was green but the associated steering dot was color coded according to its proximity to the ASE circle. Within the circle, the steering dot was red to indicate within-allowable-steering-error. Outside the circle, but within two degrees of it, the dot was yellow. Beyond two degrees, the dot was green. The radial target aspect line attached to the ASE circle was color coded depending on the nose versus tail aspect relationship between the ownship and target velocity vectors. The line was red from 270 to 90 (across the top) degrees aspect angle to indicate that the ownship nose was oriented to the target's tail. A yellow line between 90-110 and 270-250 degrees indicated an approaching neutral aspect. A green line between 110-250 degrees indicated neutral.

Dynamic launch range group. This symbology showed the PDT range and closure rate along the left side of a fixed scale. The right side of the scale showed significant launch-parameter ranges for the selected weapon. When the PDT was within the $Rmax_2$ and Rmin envelope, a TD-box- or locator-line-associated shoot cue was presented. If the PDT was between the target turn-and-run range (Rtr) and Rmin, the shoot cue symbol was flashed at 5 Hz. A break "X" symbol (not shown in Figure 1) was drawn across the center of the HMD FOV whenever the PDT range was inside Rmin.

The range bars on the dynamic launch range scale were colored to indicate the launch limitations they represented. The $Rmax_1$ bar was yellow and the $Rmax_2$, Rtr, and Rmin bars were red. The line that connected the Rtr and Rmin bars to indicate the Rtr region was also red. The dynamic target range and closure rate caret were colored to show the launch envelope region in which the target was located. The caret was green beyond $Rmax_1$ and within Rmin. Within the $Rmax_1$–$Rmax_2$ region, the caret changed from green to yellow. The caret snapped to red as the target crossed into the $Rmax_2$–Rmin region.

2.5 Scenario

The scenario was a multi-player air-to-air engagement involving hostile bombers, friendly fighters, unknown fighters, and hostile fighters. The gaming area was a 60 x 50-nm portion of the Defense Mapping Agency southwest US database, and the Truth or Consequences airport near Albuquerque, New Mexico was homeplate. The scenario involved the combined use of head-down radar functions and HMD-provided target location information to perform target acquisition, radar lock, identification, and missile launch. There were four mission phases: combat air patrol, intercept, attack (bombers and fighters), and egress. Our interest focused on the intercept and attack phases.

There were six players: the primary cockpit (ownship), two manned fighters, an autonomous friendly fighter, and two autonomous enemy bombers. The manned fighters were flown by experienced laboratory personnel via auxiliary simulator stations and changed identification (i.e., from unknown to either friendly or hostile) according to the experimental design. Their tactics were coordinated by an air-to-air tactics expert acting as an Airborne Warning and Control System (AWACS) controller (red controller). The primary cockpit was given AWACS type information by the experimenter (blue controller). The controllers viewed wall-projected God's-eye views of the gaming area and on-demand status information about each aircraft. The players communicated via an intercom that allowed the experimental participant to hear only the blue controller and everyone else to hear all other communication.

For each trial, the bombers started from one of four randomly chosen locations and then tracked directly toward homeplate, flying one mile apart in a trail formation. Five waypoints, connected to form a closed course, were used as fighter start locations. The autonomous friendly fighter, which served as a distracter for the participant, started from a waypoint adjacent (either left or right, chosen randomly) to the bomber start location and then also tracked directly toward homeplate. The manned fighters started from the waypoint adjacent to the bomber start location and opposite the friendly distracter location. As long as the manned fighters were designated "unknown," they followed the closed course counter-clockwise in formation from waypoint to waypoint at 15,000 ft (4572 m) and 480 kts. If their identification switched to friendly or hostile, they maneuvered according to the red controller's directions. Hostile fighters maneuvered aggressively against the ownship but did not fire on it. (The ownship was instructed to fly nonetheless as if hostiles could fire.) Friendly fighters maneuvered to cause confusion.

2.6 Rules of engagement

Starting from homeplate at 15,000 ft (4572 m) and 480 kts, the ownship pilot was directed by the blue controller via radar vectors toward the two approaching bombers with instructions to identify and shoot them down. While the ownship maneuvered, the blue controller gave snap-look location information about other "unidentified" targets in the area. These targets appeared on the ownship radar when they were within the coverage volume. The ownship pilot could select one PDT at a time using either the conventional radar display (which had a 40-mile, or 64-km, range and ± 60-degree field-of-regard) or the HMD.

The ownship pilot was instructed to monitor the other aircrafts' movements during the bomber attack. Once the bombers were defeated, the ownship concentrated on the secondary targets. During the bomber-attack mission phase, the manned fighters followed the prescribed waypoint route and the ownship IFF, which was available only on the HMD, showed them as unknowns. Once they reached their first waypoint (this took 3 to 5 minutes), their IFF indications could change. The ownship rules of engagement depended on the indications. Friendly targets could be ignored, and if only friendlies remained, the ownship was to egress toward homeplate. If the IFF was unknown and the target was approaching homeplate, the ownship was to intercept and track it. If the unknown turned away from homeplate, the ownship was to egress. If the IFF was hostile, the ownship was to shoot the target down. The ownship was also to egress if all hostiles were shot down or all eight missiles were used. The trial ended when egress commenced.

2.7 Procedure

For training, each participant read instructions, examined color figures of the symbology set, listened to an oral description of the task, free-flew for 30 minutes to become familiar with the simulation, and then experienced several full-scenario practice trials. Questions were addressed as they arose, both during training and experimental trials.

Each participant completed all four 1-hour experimental sessions in one day, with rest pauses given as needed and a lunch break at the halfway point. Each session consisted of 8 trials, yielding a total of 32 trials per participant. The use of color-coded HMD symbology alternated across sessions: Even-numbered participants began with color-coded symbology and odd-numbered participants began with monochrome. Thus, HMD color was a within-subjects variable. The start locations of the bombers, manned aircraft, and distracter friendly, and also the manned aircraft identifications (i.e., both switch from unknown to friendly, both switch to hostile, one switches to friendly and the other switches to hostile, or both remain unknown) were balanced across trials for control purposes, but were not factors in the subsequent analyses. All simulation data parameters were recorded at 5 Hz and all trials were videotaped.

2.7.1 Subjective feedback

After completing all trials, the pilots filled out a questionnaire designed to collect ratings and open-ended comments. Of the most interest were questions related to the potential for the HMD and color coding of HMD symbology to aid air-to-air targeting tasks. Potential was rated using the scale shown below.

None	Little	Some	Significant	Great
1	2	3	4	5

The first set of items asked the pilots to: (1) Rate the overall potential for HMD-presented information to enhance performance for an air-to-air task; (2) Rate the potential for HMD-presented target information to enhance target location and tracking tasks; and (3) Rate the potential for HMD-presented ownship information (attitude, airspeed, etc.) to enhance primary flying tasks while acquiring and managing targets. In a yes/no general feedback format, pilots were asked if there was anything potentially confusing about the symbology they experienced.

The second set of items asked the pilots to rate the potential for color coding to aid air-to-air targeting tasks: (1) Compared to the all-green symbology set, rate the potential of the color coded HMD symbology you saw to enhance overall mission success; (2) Rate the potential for the color coding you saw to enhance performance compared to the all-green symbology for determining levels of weapons launch readiness; and (3) Rate the potential for the color coding you saw to enhance performance compared to the all-green symbology for target identification and IFF tasks.

The pilots indicated their preferences for the three different color-coding approaches for the simulated mission by responding to questions such as:

- Do you feel that color coding of HMD symbology has potential operational benefit? (yes/no)

- Do you feel that the addition of color coding to the HMD symbology you saw had an effect on operational situation awareness? (yes/no)
- Do you feel that the addition of color coding to the HMD symbology you saw had an effect on operational workload? (yes/no)
- Do you feel that the addition of color coding to the HMD symbology you saw had any other effects worth mentioning?

Finally, the pilots were asked if the scenario was a good one for testing the color codes. If the answer was no, they were asked to suggest how it could be improved.

2.7.2 Performance data

For each launch, we computed PDT time prior to a launch and the target's range at the time of the launch. These PDT times showed pronounced positive skew, so we log-transformed them. We sorted launches into three probability-of-kill (Pk) categories according to the shoot-cue indications that were present at launch time: A flashing shoot cue denotes the highest Pk, a nonflashing cue denotes medium Pk, and an absent cue denotes low Pk. We also differentiated between launches against bombers and launches against hostile fighters because these target types call for different attack and maneuvering tactics. We calculated a mean $\log_{10}$ PDT time and mean target range for each participant x Pk x target-type x HMD-color combination. We dropped cells that had fewer than two observations. One-way ANOVAs, using HMD-color as the main effect, were then performed for each combination of Pk and target-type, using only those participants who had no missing cells.

3. RESULTS

3.1 Subjective findings (general):

The pilots indicated that the overall potential for HMD-presented information to enhance performance for an air-to-air task was great (mean rating = 4.66). Likewise, the potential for HMD-presented target information to enhance target location and tracking tasks was reported as great (mean rating = 4.48). HMD-presented ownship information (attitude, airspeed, etc.) was rated as having some potential to enhance primary flying tasks while acquiring and managing targets (mean rating = 3.17). Seven of the 12 pilots reported that the HMD symbology was potentially confusing.

Comments: (regarding the potential for confusion)

1. *"Too much lag in the tracker."*
2. *"The HMD and HUD show critical information in different ways. This is unacceptable."*
3. *"[This] ownship information is unusable."*
4. *"Head position information is not only useless, it is actually confusing."*
5. *"[I] don't need helmet elevation and azimuth [information]."*
6. *"Too many numbers for practical use."*
7. *"Too much information."*

3.2 Subjective findings (color coded symbology):

Compared to the all-green symbology, the color coded HMD symbology was rated as having some to significant potential to enhance overall mission success (mean rating = 3.50). Using color for determining levels of weapons launch readiness was rated as having significant potential (mean rating = 4.00). The use of color to enhance performance for target identification and IFF tasks was rated as having between some and significant potential (mean rating = 3.50).

Comments:

1. *"I would fire immediately in range rather than have to evaluate."*
2. *"The color shoot cue has the most effect."*
3. *"If the potential exists to field a color HMD, fielding a monochrome HMD would be tragic."*
4. *"Color does not save a confusing symbology but it highlights information that otherwise would be lost."*
5. *"I found target ID much simpler with color."*

3.3 General comment and yes/no questions.

All 12 pilots agreed that color-coded HMD symbology has potential operational benefit. Also, all 12 pilots indicated that color-coded HMD symbology had an effect on operational situation awareness. Ten pilots indicated that color HMD symbology had an effect on operational workload.

<u>Comments</u>:

1. *"A tremendous amount of potential. It will cut down on fratricide."*
2. *"Color is easier to understand but I'm not sure of the impact on operational performance."*
3. *"Helped define threat earlier than digital."*
4. *"Marginally quicker processing of information."*
5. *"Color improved rapid SA. ID and Launch parameters were immediately obvious."*
6. *"Used the right way, color could reduce the need for alphanumerics."*
7. *"SA and workload improved but red is sometimes hard to read."*
8. *"Color was effective in that you knew WEZ info without interpretation, but the advantage was minimal. In a turning fight, that may mean the difference between having a shot or not."*
9. *"[Color] turned shot employment into more analog instantaneous recognition of valid parameters."*

3.4 Scenario

Nine of the 12 subject pilots reported that the scenario was good for testing the color vs. monochrome HMD symbology. Three reported that the scenario could be improved by making the task more complex and including a complete complement of ownship weapons.

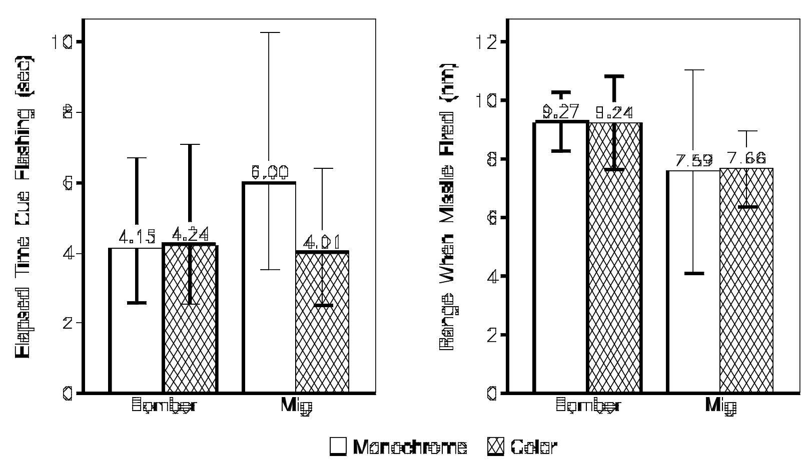
3.5 Target identification

We expected that friendly and unknown targets would be fired on occasionally and these errors might be less frequent when the IFF symbology was color coded. There were four launches against friendly targets and seven against unknowns, but upon review of the videotapes, none were attributable to HMD color.

We also thought participants might identify targets quicker when color-coded IFF was available. To test this hypothesis, we calculated PDT times on friendly targets when a hostile was present—a situation that called for identifying the friendly quickly and moving on to the critical task of shooting the hostile. Most of these PDT times were less than 10 s, but 20 exceeded 20 s and were deleted as outliers, leaving 249 observations from which we calculated a mean for each participant x HMD-color combination. Mean PDT times for monochrome and color IFF were 6.8 and 6.5 s, respectively. A one-way ANOVA showed that this difference is non-significant, $F(1,11) = 0.32$, $p = 0.5848$.

3.6 Launch solution performance

<u>Flashing shoot cue.</u> PDT time for this case was computed as the difference between the time at which the cue started flashing and the time at which the launch occurred. For bomber launches, 7 participants had no missing cells; for hostile fighter launches, 11 had no missing cells. The mean $\log_{10}$ PDT times and mean target ranges for these participants are shown in Figure 2. The ANOVAs showed that HMD color had no significant effect on PDT time for bombers, $F(1,6) = 0.03$, $p = 0.8578$, but color coding reduced PDT time significantly for hostile fighters, $F(1,10) = 11.08$, $p = 0.0076$. The difference



between the reverse-transformed (i.e., geometric) means for the fighters is 1.24 s. HMD color had no significant effect on target range at launch time for bombers, $F(1,6) = 0.01$, $p = 0.9431$, or hostile fighters, $F(1,10) = 0.05$, $p = 0.8262$.

Figure 2. Geometric mean PDT times and mean target ranges for launches against bombers and hostile fighters when the shoot cue was flashing. Whiskers show standard deviations.

Nonflashing shoot cue. PDT time for this case was computed as the difference between the time at which the cue came on and the time at which the launch occurred. For bomber launches, 10 participants had no missing cells; for hostile fighter launches, there were only 7 shots in the monochrome condition and 14 in the color-coded condition, so we did not perform ANOVAs for fighter launches. The mean $\log_{10}$ PDT times and mean target ranges for bombers are shown in Figure 3. The ANOVAs showed that color coding reduced PDT time significantly, $F(1,9) = 5.85$, $p = 0.0387$, and increased the target range at launch time significantly, $F(1,9) = 6.02$, $p = 0.0366$. The differences between the PDT-time geometric means and target-range means are 1.58 s and 1.17 nm, respectively. A 1.17-nm difference has no practical effect on Pk for a non-maneuvering target, so although there is presumably a causal relationship between the reduced PDT times and increased target ranges, we conclude that the participants shot sooner without sacrificing shot quality in the color-coded condition. The sparse data for fighter launches show the same trend.

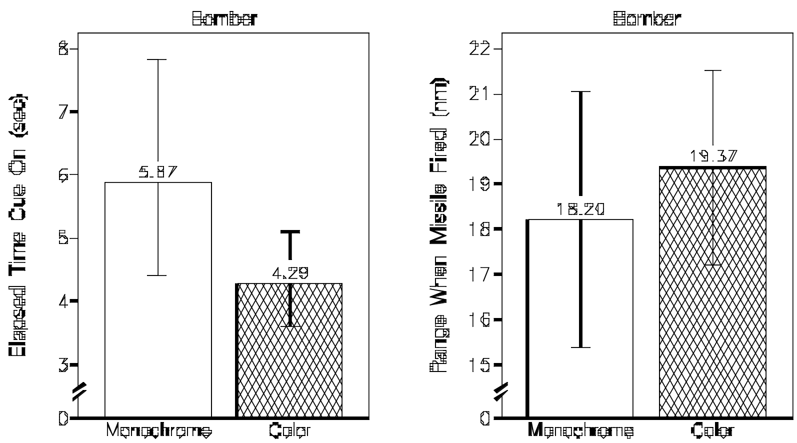


Figure 3. Geometric mean PDT times and mean target ranges for launches against bombers when the shoot cue was on but not flashing. Whiskers show standard deviations.

Shoot cue off. There were not enough launches for this case to permit reasonable ANOVAs. The data resemble those for the nonflashing shoot cue, though.

4. DISCUSSION

One purpose of this project was to collect military pilots' opinions regarding the potential of color-coded HMD symbology to produce an operational benefit, compared to performing the same task with monochrome symbology. Shape coding and the functionality of the symbology was held constant for purposes of comparison. A reasonably complex and realistic air-to-air engagement scenario was employed for the evaluation. Consistent with past findings, the pilots overwhelmingly reported that HMD technology has potential to aid the air-to-air targeting task. The pilots also reported that the addition of color furthered the performance enhancing potential of the HMD. Also consistent with our past findings, the "red means shoot" color code was deemed effective.

Our objective results show that the "red means shoot" code, when applied to the VCATS weapons symbology, produced significantly faster shots against fighters and bombers, without degrading Pk. For fighter targets, this advantage was demonstrable only for flashing shoot cues whereas, for bomber targets, it was demonstrable only for nonflashing shoot cues. This difference almost certainly reflects a difference in tactics: Military pilots know that launches against agile fighters should be delayed until the best possible launch solution is available, whereas launches against bombers can be successful under less optimal conditions. Furthermore, in our scenario, it was important to shoot the bombers quickly and move on to the fighters.

Our best estimates of the average time reductions due to color coding are 1.24 and 1.58 s against fighters and bombers, respectively, albeit for different launch solutions. These might not seem like substantial differences, but in contemporary air-

to-air combat, even fractions of a second can have life or death consequences. Viewed from this perspective, the time savings demonstrated here are impressive, and even if they proved to be only half as great in the more complex environment of real combat, they would still be sufficient to make color HMDs worth serious consideration.

It is natural to wonder whether the advantage we seem to have found for color coding is related to luminance contrast rather than color. Clearly, the contrasts we were able to produce are mostly below the minima recommended, for example, for visual display terminals[13,14], and it might be that it was simply harder to read the monochrome green symbology. Examination of our figures, however, shows that most launches occurred at least several seconds after the shoot cue appeared, which seems too long a delay if the pilots were merely shooting as soon as an appropriate cue became legible. We believe the advantage of color coding was that it eliminated the need to read or even foveate the symbology at all, freeing the pilots to focus their vision and attention on other matters that influence the decision to shoot and thus recognize a good opportunity quicker.

Our next step will be to re-design the symbology to try to further exploit the apparent advantages of color coding. A similar evaluation will be performed to compare the new format to the baseline color symbology.

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